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PERFORMANCE MEASUREMENTS OF A PILOT SUPERCONDUCTING SOLENOID MODEL CORE FOR A WIND TUNNEL MAGNETIC SUSPENSION AND BALANCE SYSTEM

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ABS: The results of experimental demonstrations of a superconducting solenoid model core in the Southampton University Magnetic Suspension and Balance System are detailed. Technology and techniques relevant to large-scale wind tunnel MSBSs comprise the long term goals. The magnetic moment of solenoids, difficulties peculiar to superconducting solenoid cores, lift force and pitching moment, dynamic lift calibration, and helium boil-off measurements are discussed.

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CONTENTS

ABBREVIATIONS

MSBS	Magnetic Suspension and Balance System
LMSBS	Large magnetic suspension and balance system
SUMSBS	Southampton University magnetic suspension and balance system
E/M	Electromagnet
LHe	Liquid Helium
GHe	Gaseous Helium
NbTi	Niobium-titanium (superconductor)

1. INTRODUCTION

This report details the results of experimental demonstrations of a superconducting solenoid model core in the Southampton University Magnetic Suspension and Balance System with limited technical preamble included to provide an appropriate background. The work forms part of a long term research program at Southampton University, principally sponsored by NASA Langley Research Center via Grant NSG-7523, aimed towards developing technology and techniques relevant to large-scale wind tunnel MSBSs.

One method of substantially reducing the currently prohibitive projected costs of a LMSBS (Ref. 1) is to devise model core concepts capable of providing greater magnetic moment per model than conventional ferromagnetic cores. The dominant cost of LMSBSs appears at present to lie in the array of suspension electromagnets and their ancilliaries but, for given aerodynamic force and moment requirements, the size, hence cost, of these items falls as the available model magnetic moment rises. Persistent high field superconducting solenoids have been proposed as one possible concept for high magnetic moment model cores.

1.1. Magnetic moment of solenoids

If a uniform solenoid is compared with a solid ferromagnetic core of equivalent overall dimensions and total magnetic moment, as illustrated in Fig. 1, it is easily shown that:

$$M_{EQ} = \frac{I_D \mu_o (r_2^3 - r_1^3)}{3r_2^2} \qquad .....(1)$$

M_{EQ} = equivalent core magnetization, in Tesla

μ_o = permeability of free space = $4\pi \times 10^{-7}$ Hm^{-1}

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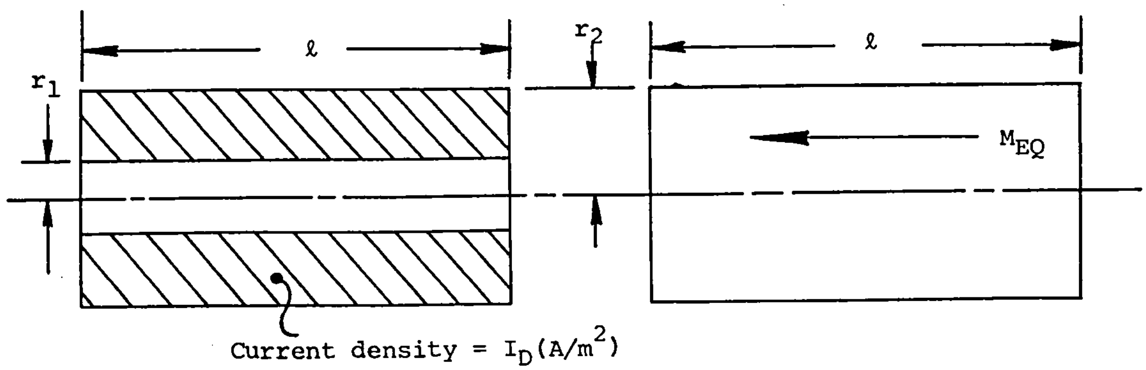


Fig. 1 Equivalent solenoidal and ferromagnet cores

Now, the highest available value of M_{EQ} with ferromagnetic materials (vanadium permendur) is around 2.4 Tesla and a reasonable value of current density for modern superconductors might be 2×10^8 A/m^2. Assuming, r_1 to be small and solving for r_2:

$$r_2 \simeq 29\text{mm (to equal ferromagnetic performance)} \qquad .....(2)$$

Despite the fact that (2) makes no allowance for the thermal insulation etc. required for a superconducting solenoid, it is seen that since a typical fuselage radius for an 8 foot wind tunnel might be 75mm (transport type) and $M_{EQ} \propto r_2$ with r_1 small, the concept appears to have some potential.

1.2. Difficulties peculiar to superconducting solenoid cores

The obvious method of cooling the superconductor is immersion in liquid helium (LHe). In vented dewars there will be a slow release of boil-off gas which, with the model in suspension, may be aerodynamically unacceptable. Sealed dewars are technically feasible but have not yet been studied in this application.

With the solenoid in persistent mode, the current, hence magnetic moment, is not fixed. By straightforward induction, the magnetic fields applied to support and restrain the model may cause changes in the solenoid current. Losses due to residual resistance of winding splices or perhaps A.C. losses induced by the (time varying) external suspension fields may cause slow decay of current. The latter effects are not thought likely to be significant and could anyhow be accommodated by continuous monitoring of solenoid current with onboard instrumentation. The former effect could, however, provoke model

control instability if the short-term variations were large.

The induced solenoid currents will tend to hold the net flux linked through the solenoid constant. Since the self-created magnetic field (flux density) along the bore of the solenoid is certain to considerably exceed the maximum possible applied field (perhaps by a factor of 10), the maximum conceivable variation of model magnetic moment in this case can only be a few percent. Further, if the applied magnetic fields are suitably configured and manipulated, the net linkage of applied field with the solenoid may be kept constant, in fact zero. This is achieved by ensuring that all applied fields possess suitable symmetry such that the component of field along the axis of the solenoid exhibits a null around the solenoid's centroid. With a model in suspension at "normal" attitudes in SUMSBS, that is with the model and wind axes broadly parallel, the extensive E/M symmetry of SUMSBS naturally assures that this condition is met. A superconducting solenoid model is thus expected to be indistinguishable, with regard to control and stability characteristics, from a powerful permanent magnet core in this suspension system.

1.3. Experimental model

A proof-of-concept model was designed and constructed by the Institute of Cryogenics, University of Southampton, using a specially made but otherwise conventional solenoid supplied by Oxford Instruments Ltd., with cryostat design carried out by Mr. Yu Yuan Wu of the Institute (See Ref. 2, Figs. 2,3). Brief technical details are included here for reference.

Cryostat outside dimensions (not including fill tubes etc.)	390mm x 64mm diameter
Empty Weight (no LHe)	1.791 kg
LHe capacity	≃ 200 cc's (25 grams)
Solenoid dimensions (as Fig. 1)	ℓ = 120mm, r_2 = 23mm, r_1 = 9.45mm.
Working ampere-turns	≃ 372,400
Design life between LHe fills	3o minutes.

Normal operating procedure for this model is to cool the solenoid slowly to LHe temperature, fill with LHe (≃ 1-2 hours total elapsed time), charge the solenoid with current (5 minutes), set into persistent mode, detach all fill/vent tubes, current leads and instrumentation and suspend. No attempts were made to discharge solenoid current before the LHe was exhausted, natural

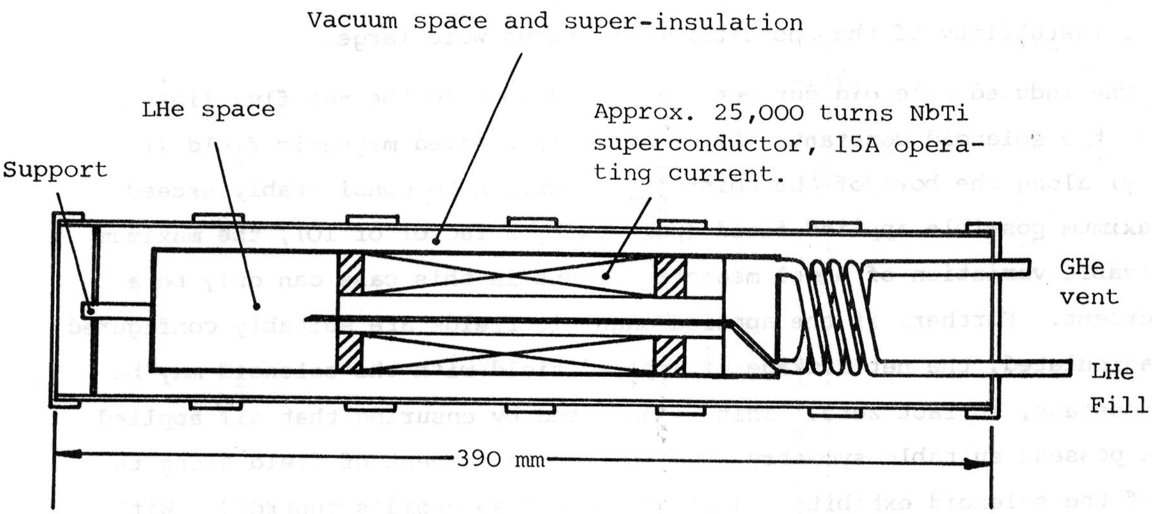


Fig. 2. Schematic cross-section of experimental superconducting solenoid model core, showing principal components

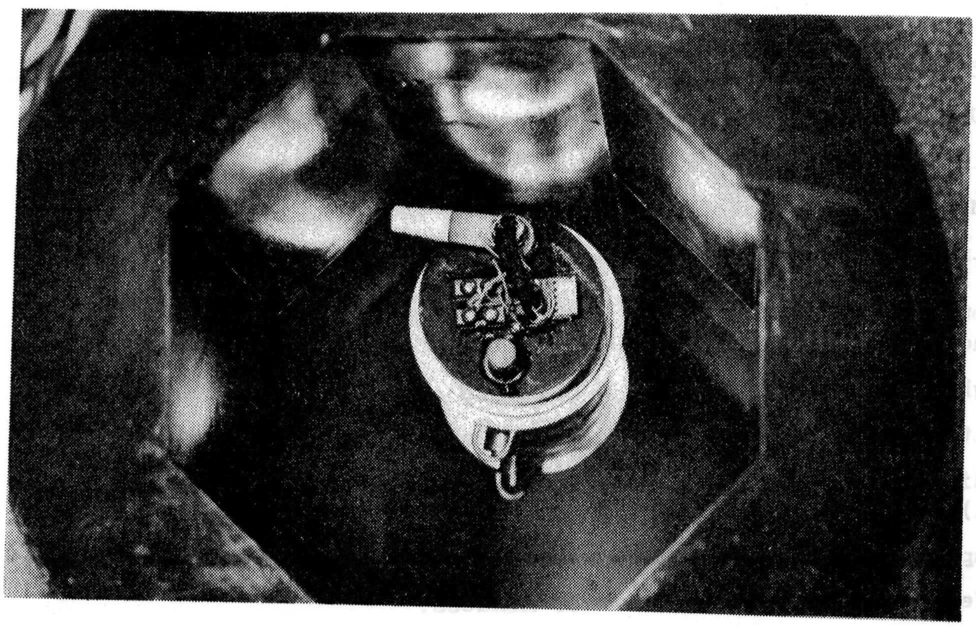


Fig. 3. Superconducting solenoid model in suspension in SUMSBS

quenching appearing perfectly safe and unspectacular.

Since the model is nominally axisymmetric and therefore has no provision for roll control, small bob weights were added to orient the model with the GHe vent near the top.

The choice of model size should be explained. Equation 1 and the weak variation of required thermal insulation thickness with scale indicate that small models of this type are relatively unattractive. A model of representative scale for, say, an 8 foot tunnel could not have been accommodated in SUMSBS and would have been unnecessarily expensive to construct and operate in a proof-of-concept study. The final overall dimensions are thus rather less than half those anticipated for the 8 foot case, although still around three times the usual scale of SUMSBS models. It is believed that no strenuous design efforts were made to maximise magnetic moment per unit volume, indeed modifying Fig. 1 and Eqn. 1 for a realistic superconducting configuration:

$$M_{EQ} = \frac{I_D \mu_o (r_2^3 - r_1^3) \ell_s}{3 \ell_F r_F^2} \quad \text{.....(1b)}$$

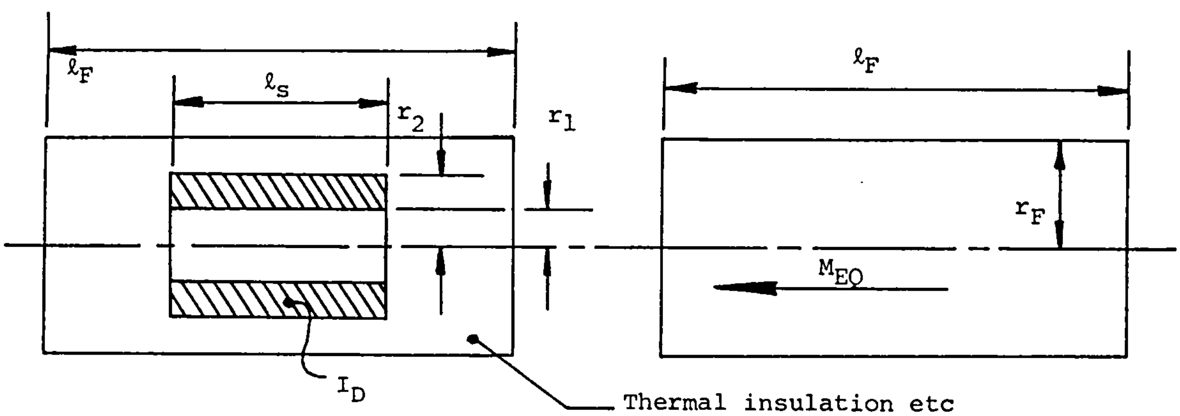


Fig. 1b Equivalent superconducting solenoidal and ferromagnetic core

and, using Eqn. 1b with the known characteristics of the experimental model, the equivalent magnetic moment based on the model's overall volume leaves:

$$M_{EQ} \simeq 0.33T$$

- only one third as good as the best permanent magnet.

The magnetic moment/unit model mass is, however, unusually high, around twice the value for the best permanent magnet, implying rather low currents required to support the model's deadweight.

2. PERFORMANCE VERIFICATION AND CALIBRATION

2.1. Lift force and pitching moment calibration

Suspension of the superconducting solenoid model in SUMSBS proved very straightforward, with only adjustments to control loop gains required to achieve stable suspension. These simply accommodate the different magnetic moment/unit mass and magnetic moment/unit moment of inertia of this model compared to standard types and were precalculated, approximate values being given below:

$$\frac{\text{Magnetic moment/unit mass (superconducting solenoid)}}{\text{Magnetic moment/unit mass ("normal" model)}} \simeq 3$$

$$\frac{\text{Magnetic moment/unit moment of inertia (superconducting solenoid, perpendicular to wind axis)}}{\text{Magnetic moment/unit moment of inertia ("normal" model)}} \simeq 1.5$$

The gains of the relevant control loops were thus adjusted by the inverse of the above figures.

The relatively large size of the superconducting solenoid model was most easily accommodated in SUMSBS by simply suspending the model unusually "high", some 31.2mm above the geometric centre of the suspension system (Fig. 4). This was expected to be a satisfactory arrangement but was later found not to be so.

Lift force and pitching moment calibrations were carried out by the following method. Loading was applied to the model by carriers and weights on two loading points, one forward and one aft, as illustrated in Fig. 5. Current levels in the four "vertical" suspension electromagnets were monitored via shunts and isolation amplifiers (see Ref. 3), all data being acquired via the on-line computer that comprises the control system (Fig. 6, Ref. 3). Limited measures were taken to ensure that model mass, magnetic and loading centres coincided (Fig. 7), it being anticipated that relatively small residual effects could be resolved by analysis. The axial location of the model in SUMSBS is not a first order effect here, model position and attitude anyway being held fixed throughout the calibration procedure by position error integrators in all control loops. Current values from the four relevant suspension E/Ms are combined to yield net "lift" and "pitch" currents, the sense of the summations being clarified in Fig. 8. It must be noted that this is not a fully comprehensive calibration procedure, ideally the lift force and

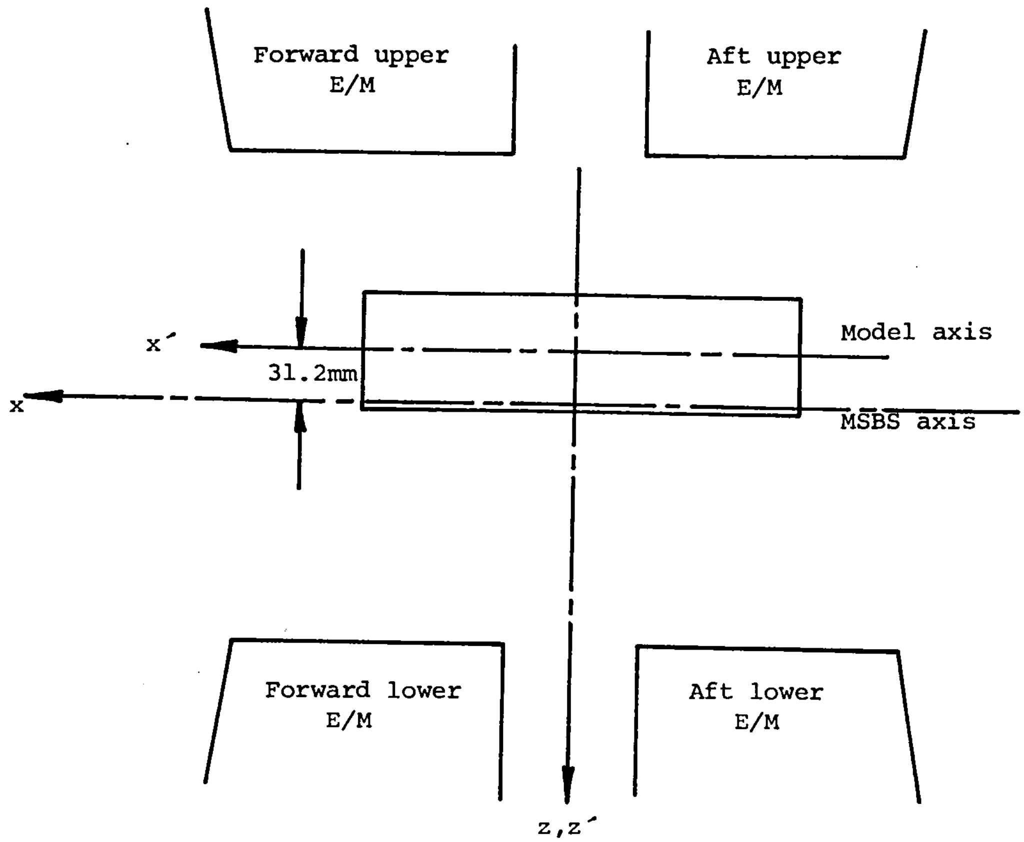


Fig. 4. Schematic vertical section of SUMSBS showing model location.

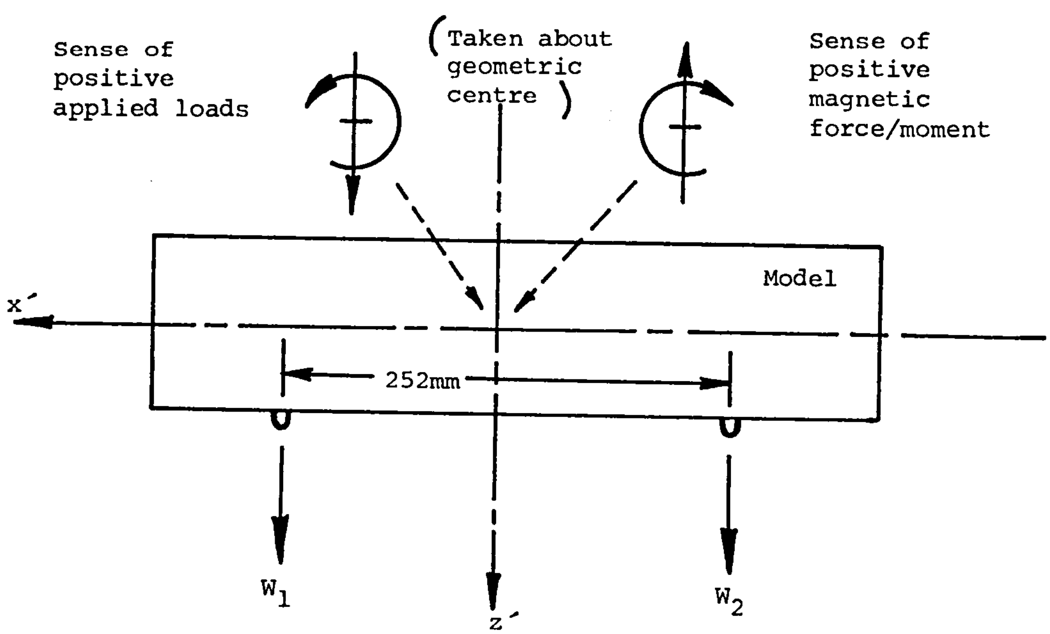
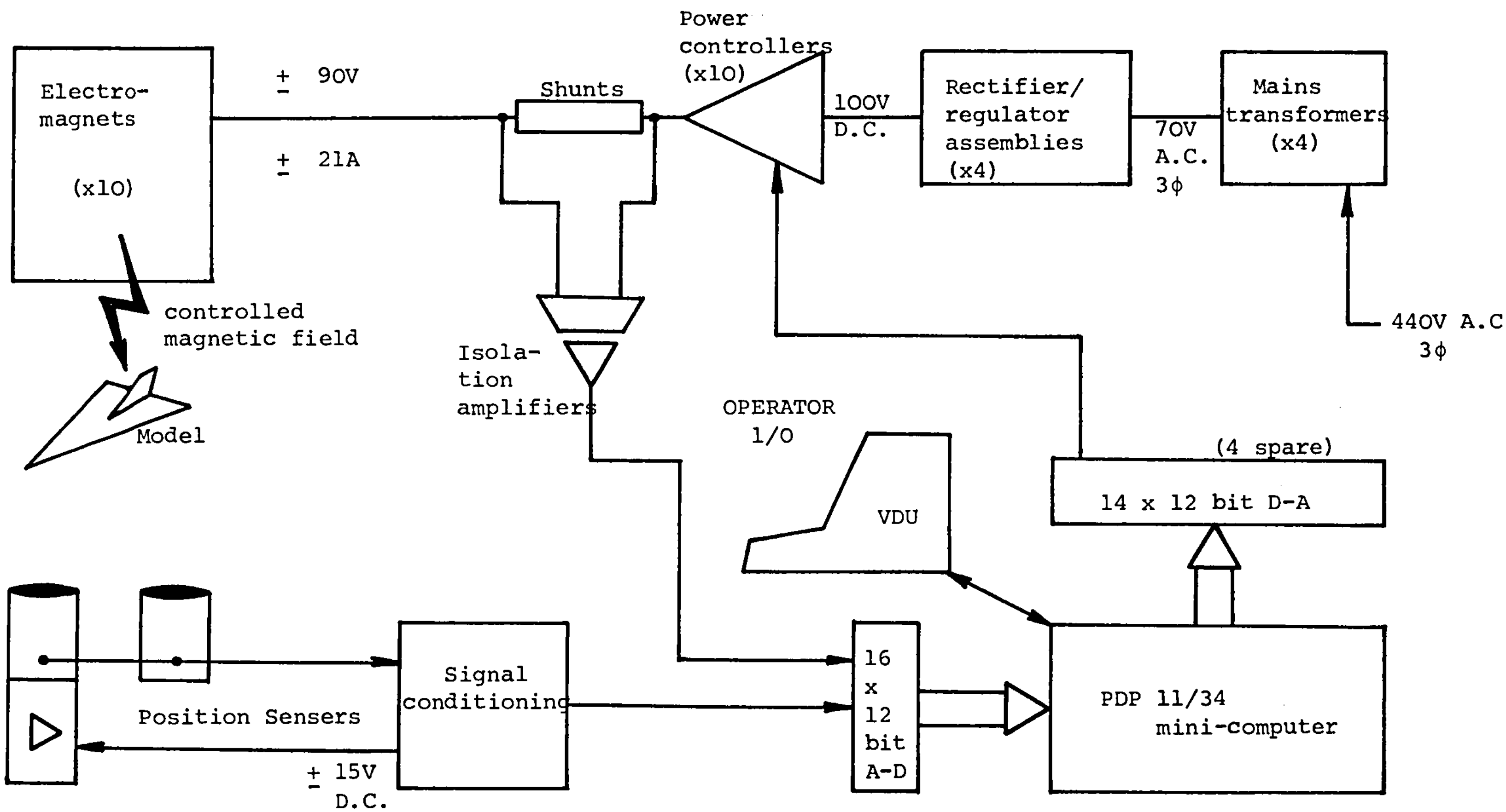


Fig. 5. Lift and pitching moment loading arrangements

Fig. 6. Schematic diagram of hardware configuration of SUMSBS



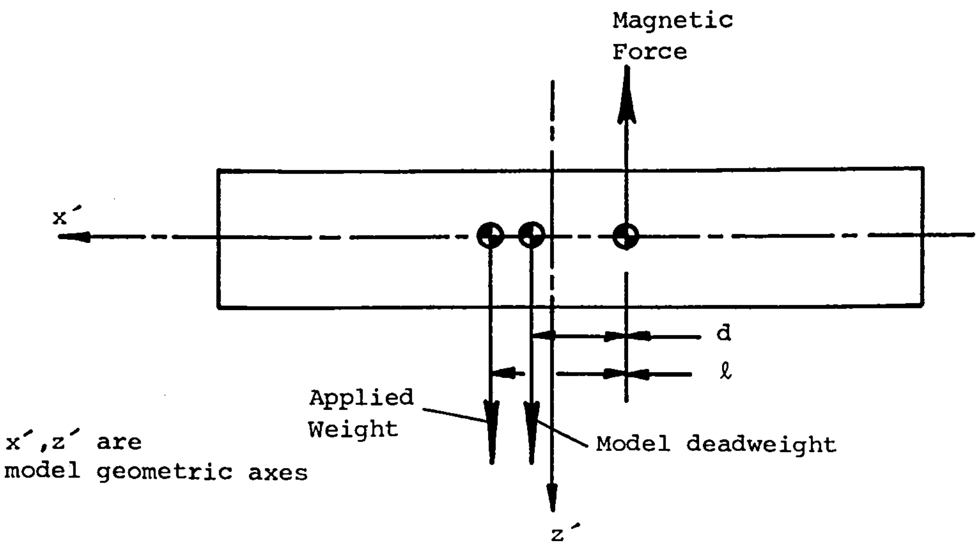


Fig. 7. Offsets of model magnetic, mass and loading centres.

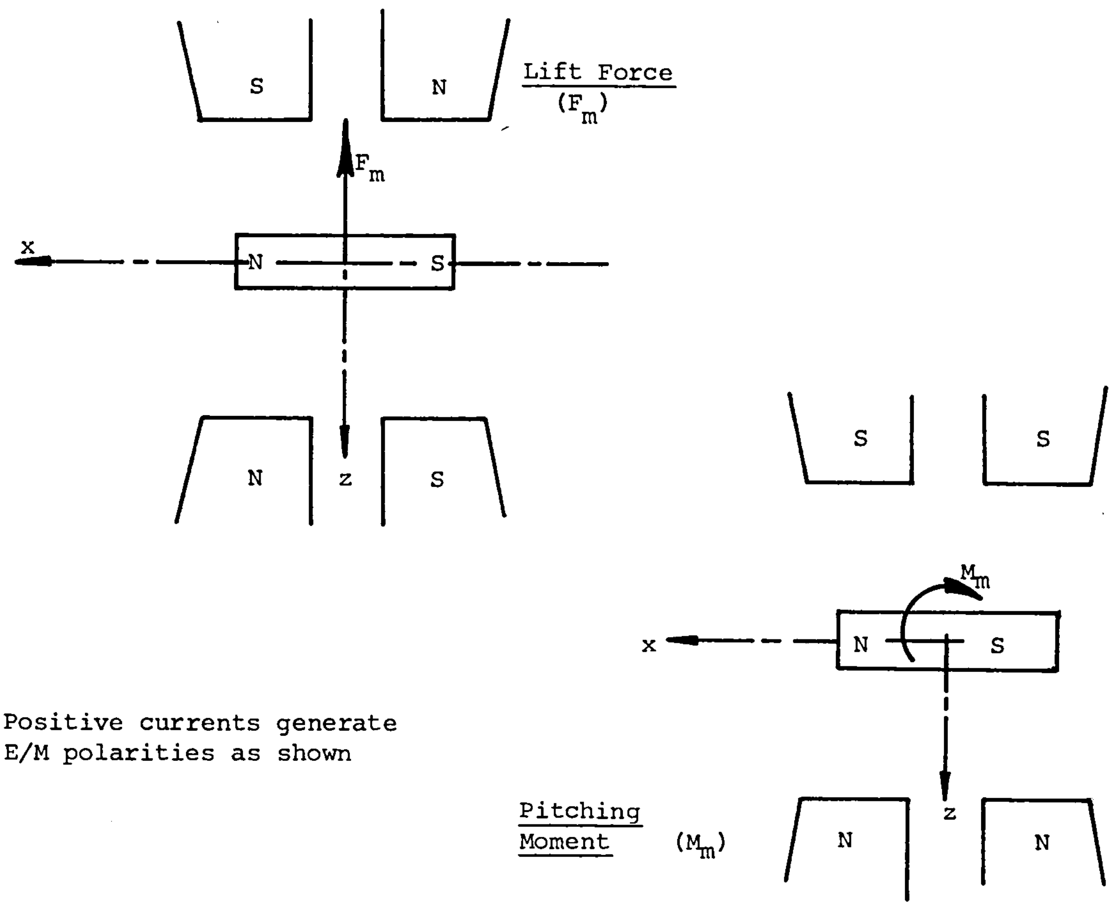


Fig. 8. Positive senses of lift and pitch current summations

pitching moment created by each individual E/M would be evaluated separately. However, it is to be expected that the influence of all four (nominally identical) E/Ms will be similar in essence, differing mainly in sign or sense, and the fixed geometry and fore-and-aft symmetry existing in this case renders valid the simplified procedure adopted. Since loading was by applied weights on 2 centres, application of pure pitching moment was impossible. The general procedures adopted were, for the lift force calibration, to increment the loading at each centre alternately, so that alternate data points feature near-zero applied moment, otherwise a substantial nose down moment, and, for the pitching moment calibration, to load the forward (nose) station only. Fig. 9 shows the lift current versus applied weight calibration, the least squares fit for slope being:

6.016 "Lift" amps/kg.force (summed over 4 E/Ms)

with exceptionally low scatter around that line.

A problem does arise, however, in that the extrapolation back to zero lift current intercepts the loading axis at around - 1082 grams, whereas the models deadweight is 1791 grams + LHe. The (full) LHe capacity is estimated at 25 g, falling of course to near zero at the end of a run, thus the model weight may be taken as 1800 grams with the variation about this value ignored. It is now believed that the off-centre suspension of the model resulted in a substantial vertical force being created by simple attraction between the model and the iron E/M cores, as illustrated in Fig. 10. The apparent lost deadweight of 718 grams is assumed to be wholly accounted for by this phenomenon. To support this argument it is noted that loading of the model into SUMSBS was quite difficult, the model tending to pull powerfully towards iron cores if moved far off centre. Such effects have never been noticed before in SUMSBS since the magnetic moment of previous models has typically been one twentieth of the value of the superconducting solenoid model and the attraction effect is expected to vary approximately as the square of model magnetic moment.

Pitch calibration could not be performed directly since pure moments could not be applied and the procedure is further complicated by the anticipated separation of magnetic and loading centres. It has already been noted that alternate data points of Fig. 9 feature near zero applied pitching moment.

Fig. 9. Lift current variation with applied weight

Least squares fit:

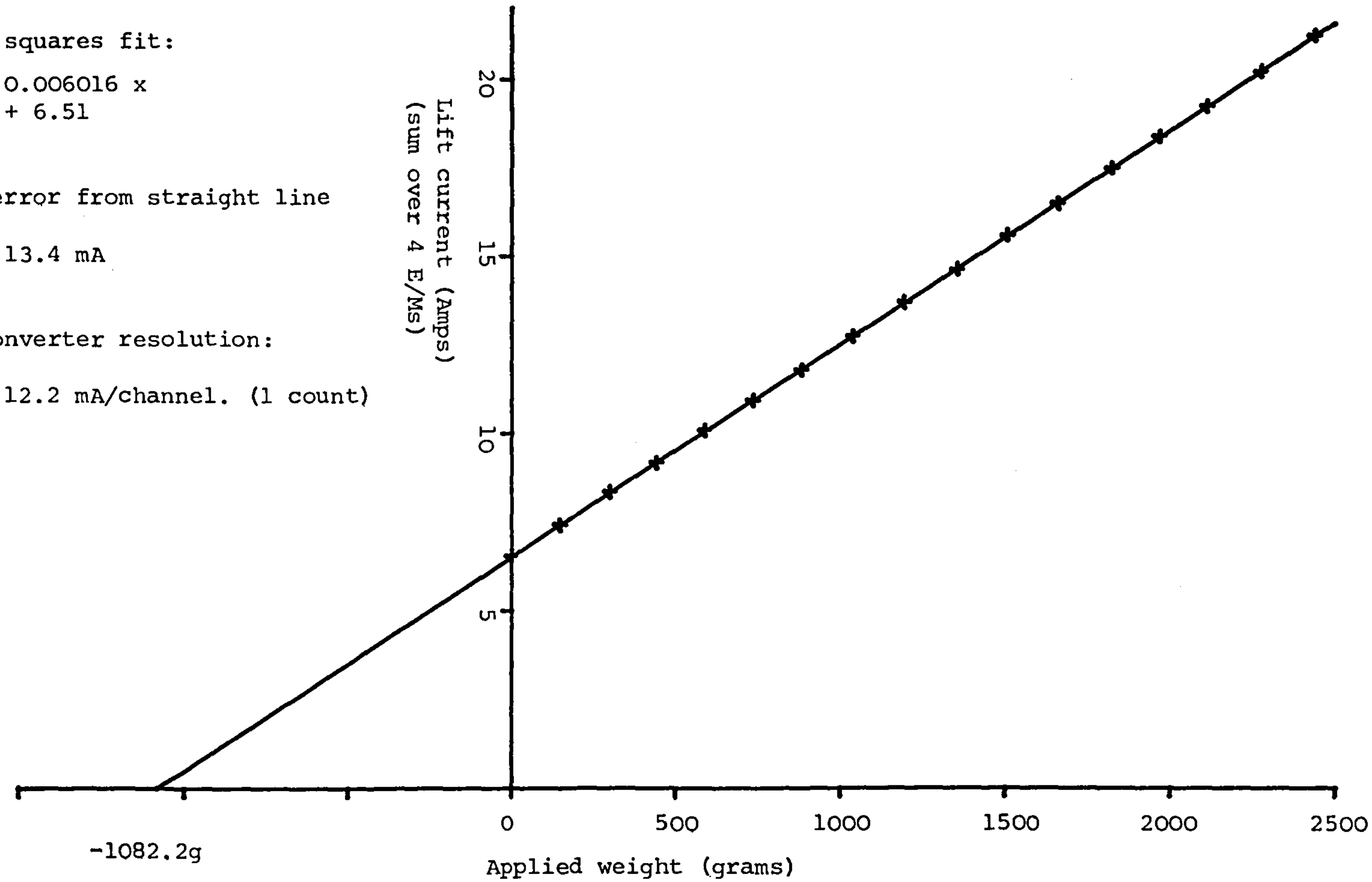
$y = 0.006016\,x$
$\quad + 6.51$

Mean error from straight line fit:

13.4 mA

A/D converter resolution:

12.2 mA/channel. (1 count)



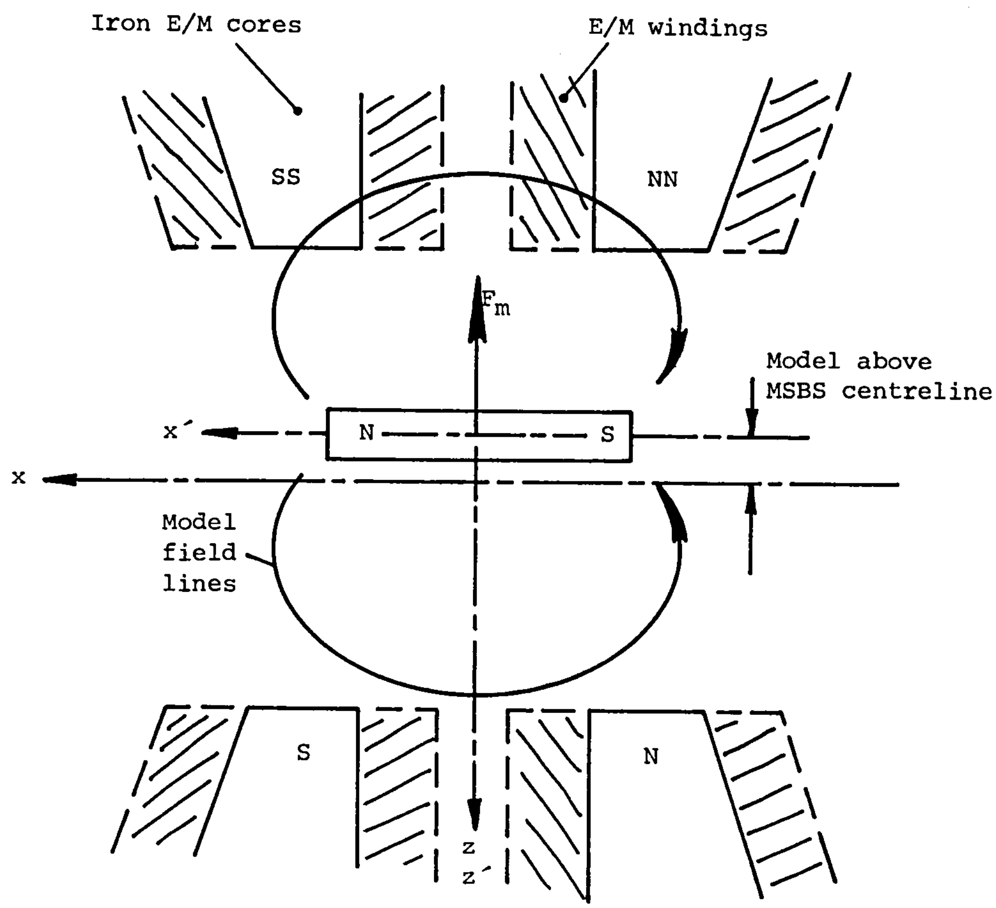


Fig. 10. Production of stray vertical force component by differential attraction to iron E/M cores.

Correcting the small pitching moment residuals using the preliminary pitch calibration of Fig. 12, leads to the pitch current versus applied weight plot of Fig. 11. The slope of the plot (again least squares fitted):

0.585 "Pitch" amps/kg. applied weight (summed over 4E/Ms)

may now be used to correct pitch calibration data for the effect of the applied weight, leading to the corrected curve of Fig. 12. Another least squares fit shows:

0.789 "Pitch" amps/kg. cm applied moment (sum over 4E/Ms)

and enables the values of d and ℓ to be resolved. The loading moment arm ℓ, is given by:

$$\frac{\text{Pitch current/kg}}{\text{Pitch current/kg cm}} = \ell = 0.74 \text{ cms}$$

and the offset of the model's centre of gravity by:

$$\text{Mass x d} = \frac{\text{Zero load pitch current}}{\text{Pitch current/kg. cm.}}$$

$$\therefore \quad d = 0.67 \text{ cms.}$$

All derived values appear reasonable.

2.2. Dynamic lift calibration

In principle it should be possible to calibrate a MSBS without application of external loading to the model. If the model characteristics and trajectory are accurately known, the inertia force terms appearing during demanded model accelerations, perhaps sinusoidal motions, wind off, can be compared with E/M currents, hence applied magnetic forces, thereby calibrating those forces. This technique has been proposed in the past but never experimentally evaluated.

Since future work in this area was planned and since oscillation of the superconducting model was considered necessary for other purposes (see

Fig. 11. Pitch current variation with applied weight

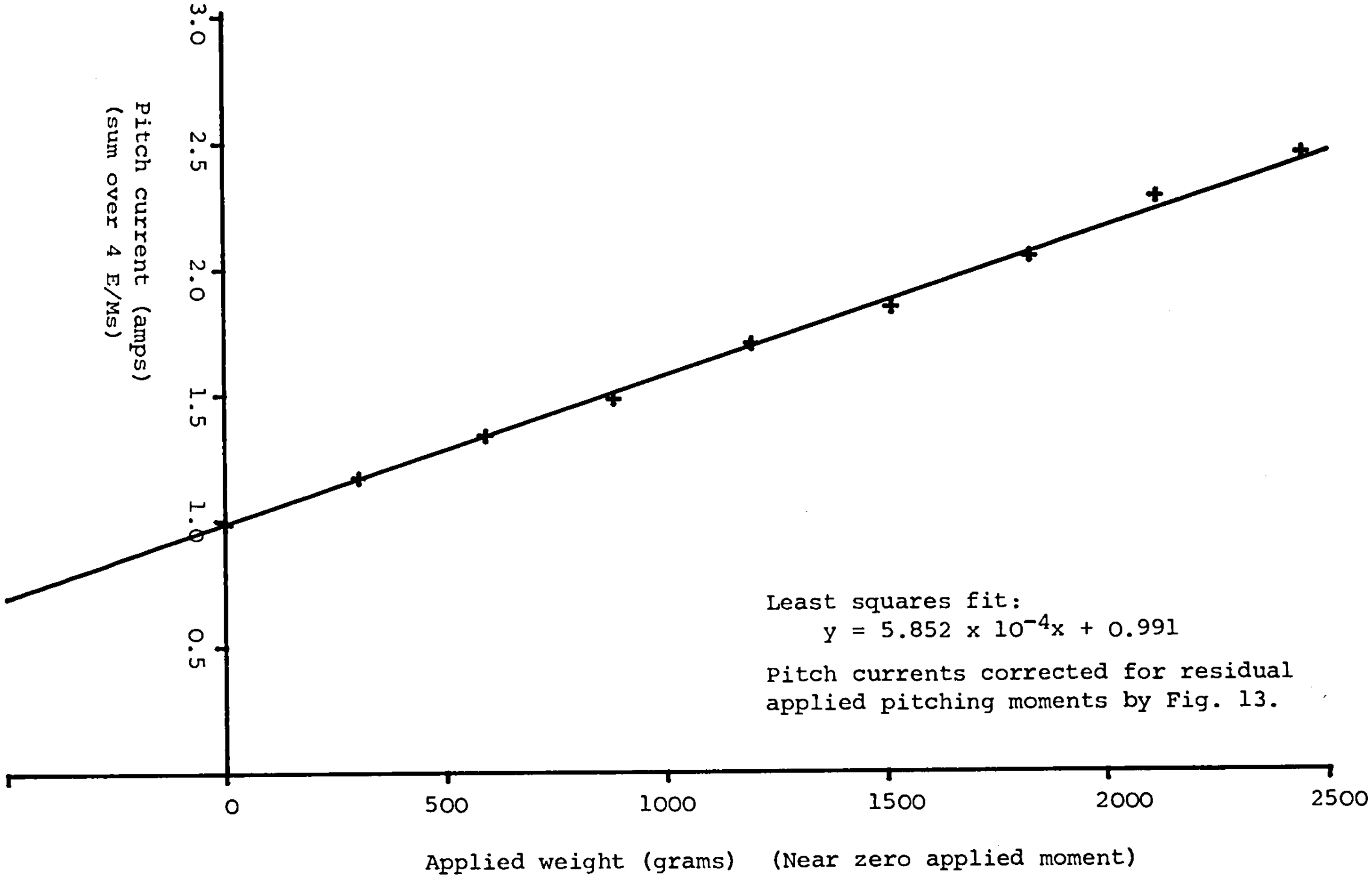
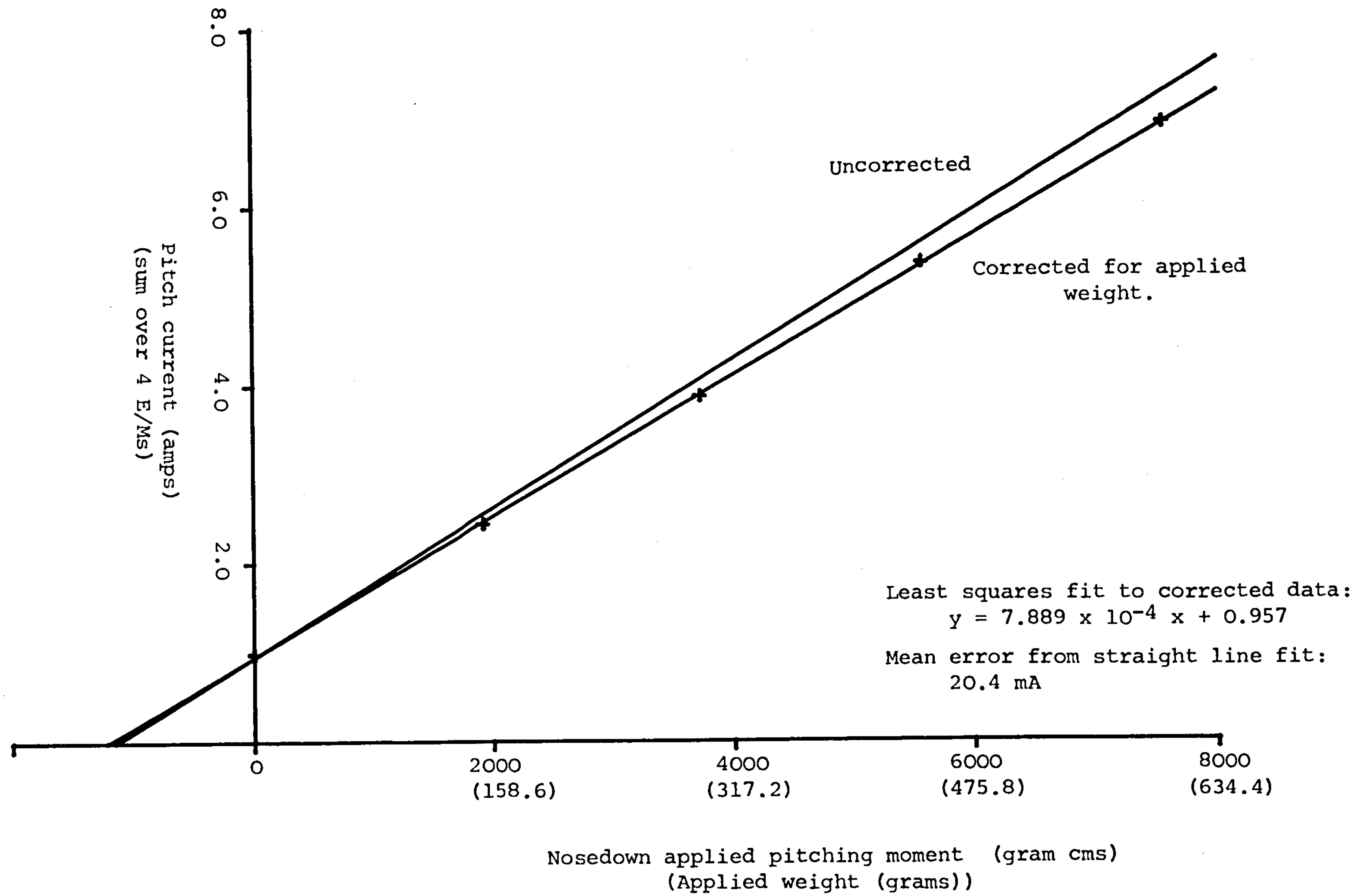
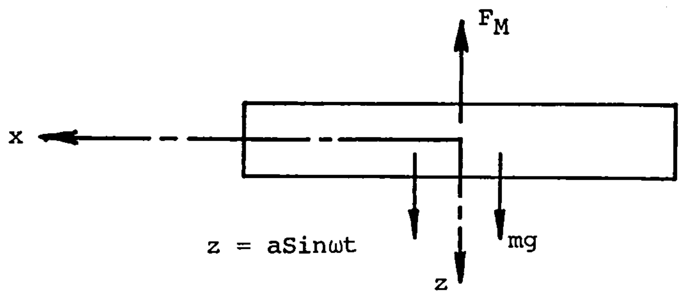


Fig. 12: Pitch current variation with applied pitching moment.



Section 2.3) it was decided to attempt a dynamic lift calibration. If the model is oscillated by applied magnetic forces in the senses shown:



then by force balance we have:

$$mg = F_M - ma\omega^2 \,\mathrm{Sin}\, \omega t$$

Resolving the magnetic force into static and dynamic components:

$$F_{M_{STATIC}} \equiv F_{MS} = mg$$

$$F_{M_{DYNAMIC}} \equiv F_{MD} = ma\omega^2 \,\mathrm{Sin}\, \omega t + \text{Other terms}$$

"Other terms" are expected to consist primarily of motion damping, which could arise from various sources, such as aerodynamics, eddy currents or LHe slosh. These terms are not easily quantified and, therefore, must be negligible for dynamic calibration to function straightforwardly. In this brief study F_{MD}, initially unknown in a genuine calibration procedure of course, is calculated from the static calibration data of Section 2.1 and compared with the inertia force ($ma\omega^2$) in order to assess the magnitude of the damping or other error terms.

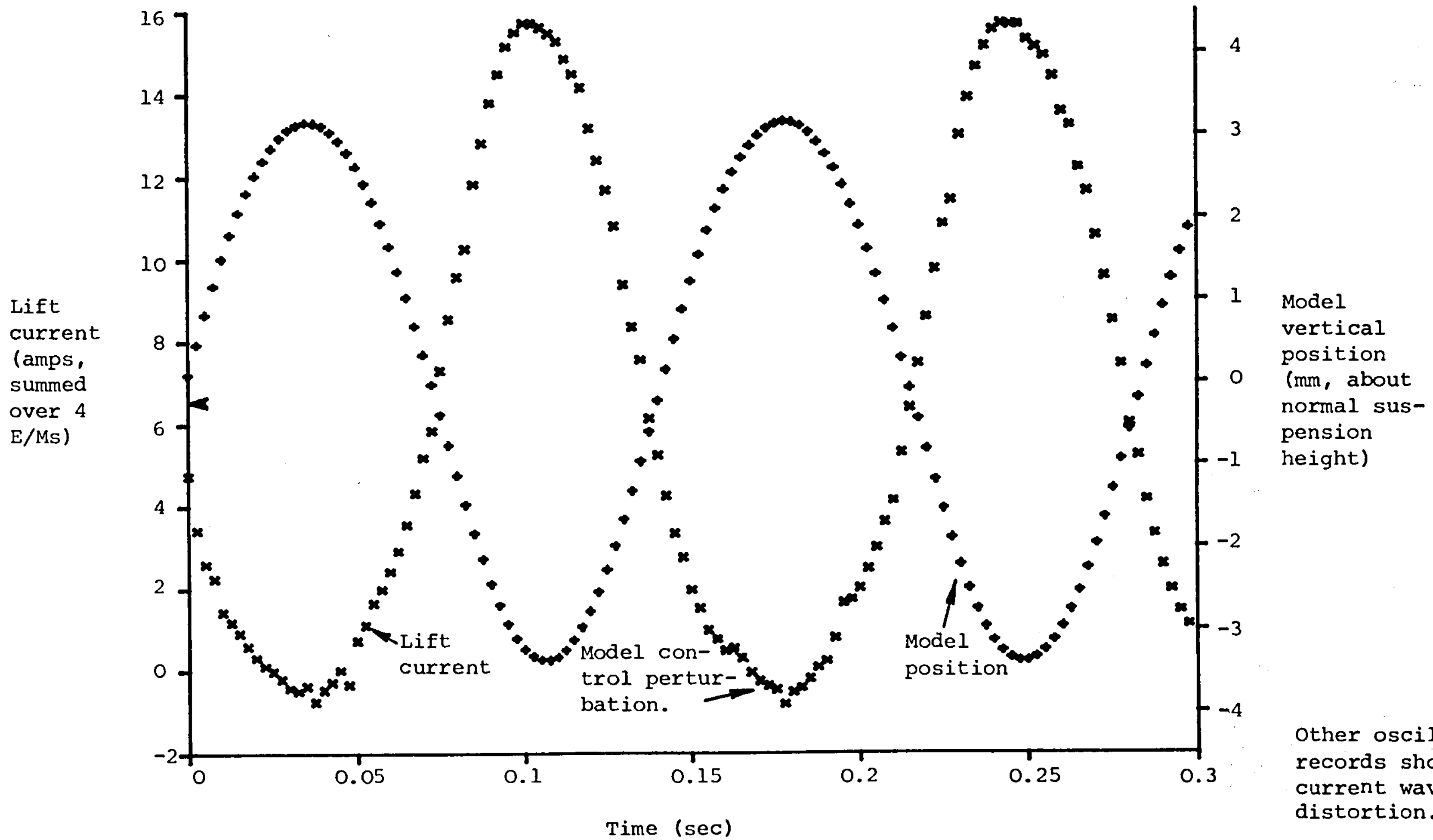
Three data sets were taken, encompassing two oscillation frequencies. Model heave position and vertical E/M currents were monitored at 400 samples/sec. over two or three periods of oscillation. Position and current fluctuations were approximate sinusoids (Fig. 13), the relevant amplitudes being estimated by numerical fitting of a sinusoid of the same frequency. Section 3 includes discussion of the distortion of the current waveform of Fig. 13. Using a position sensor calibration performed with a dummy model on a vertical vernier transverser (Fig. 14) and the static lift current calibration from Section 2 we have:

Osc. No.	No. periods analysed	Freq. (Hz)	Heave amplitude (a, mm)	$ma\omega^2$ (N)	F_{MD} (N)	$F_{MD}-ma\omega^2$ (N)
1	2	4.687	3.31	5.17	7.27	2.10
2	2	4.687	3.78	5.90	8.28	2.38
3	3	7.031	3.30	11.59	13.78	2.19

Fig. 13: Typical vertical position and lift current time histories during oscillation.

Data is first 0.3 secs (> 2 cycles) from Oscillation 3 (7.031 Hz)

◄ shows D.C. current to suspend (6.51A).



Other oscillation records show less current waveform distortion.

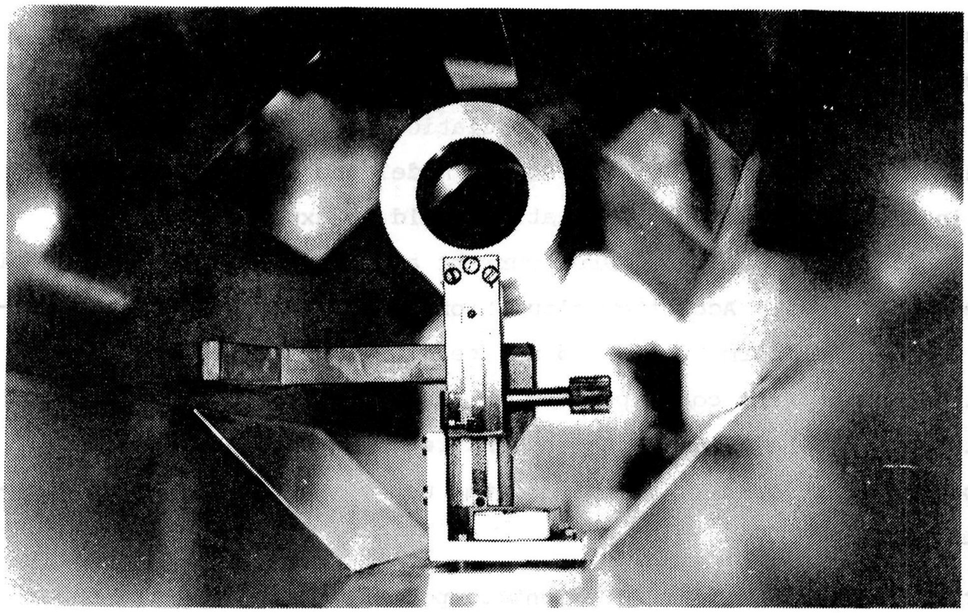


Fig. 14: Vertical translation calibration model.

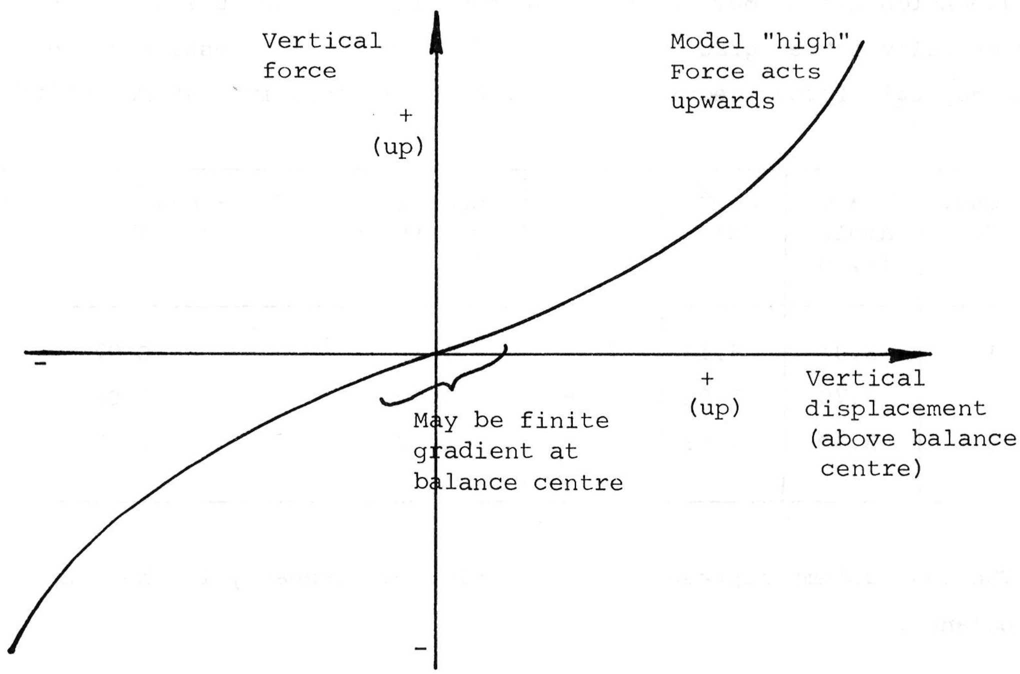


Fig. 15: Expected variation of stray vertical force component

The last column represents a discrepancy between inertia and dynamic magnetic forces and should be ideally be zero. One obvious possible source of the large discrepancies observed is a modulation of the stray lift force component created by the attraction between the model and iron E/M cores, as discussed in Section 2.1.* Such modulation would be expected to be destabilizing, that is requiring increased current amplitudes to drive the motion, as illustrated in Fig. 15. Accurate calculation of this effect is not possible here but the general form of Fig. 15 may be estimated and scaled to fit the one available data point corresponding to the stray steady lift force already mentioned. At the frequencies encountered here the iron cores are expected to behave near ideally, justifying the use of static data in a dynamic calculation.

The vertical field and field gradient components created by the superconducting solenoid may be calculated to reasonable accuracy using the computer program FORCE (Fig. 16, see Ref. 3). If the vertical component of magnetization of the iron E/M cores is assumed to vary with the vertical component of solenoid field at a suitably chosen core tip centroid and if the vertical force component is then assumed to vary as the product of the magnetization and the vertical gradient of the vertical field of the solenoid, taken about the same centroid, the estimated variation of total vertical force with solenoid suspension height may be obtained from Fig. 16, and is shown in Fig. 17. The numerically fitted gradient of Fig. 17 is now used to estimate the extra applied magnetic forces required to overcome this negative natural stiffness.

Osc. No.	Heave ampl. (a,mm)	$ma\omega^2$ (N)	F_{MD} (N)	Negative stiffness (N)	F_{MD} - $ma\omega^2$ - stiffness (N)
1	3.31	5.17	7.27	1.13	0.97
2	3.78	5.90	8.28	1.29	1.09
3	3.30	11.59	13.78	1.12	1.07

The last column represents an unresolved discrepancy in the overall force balance.

*This effect is NOT representative of future large MSBSs, which are unlikely to have iron E/M cores.

Fig. 16: Vertical field and field gradients in region of iron E/M cores due to superconducting model

"Calculations by FORCE"

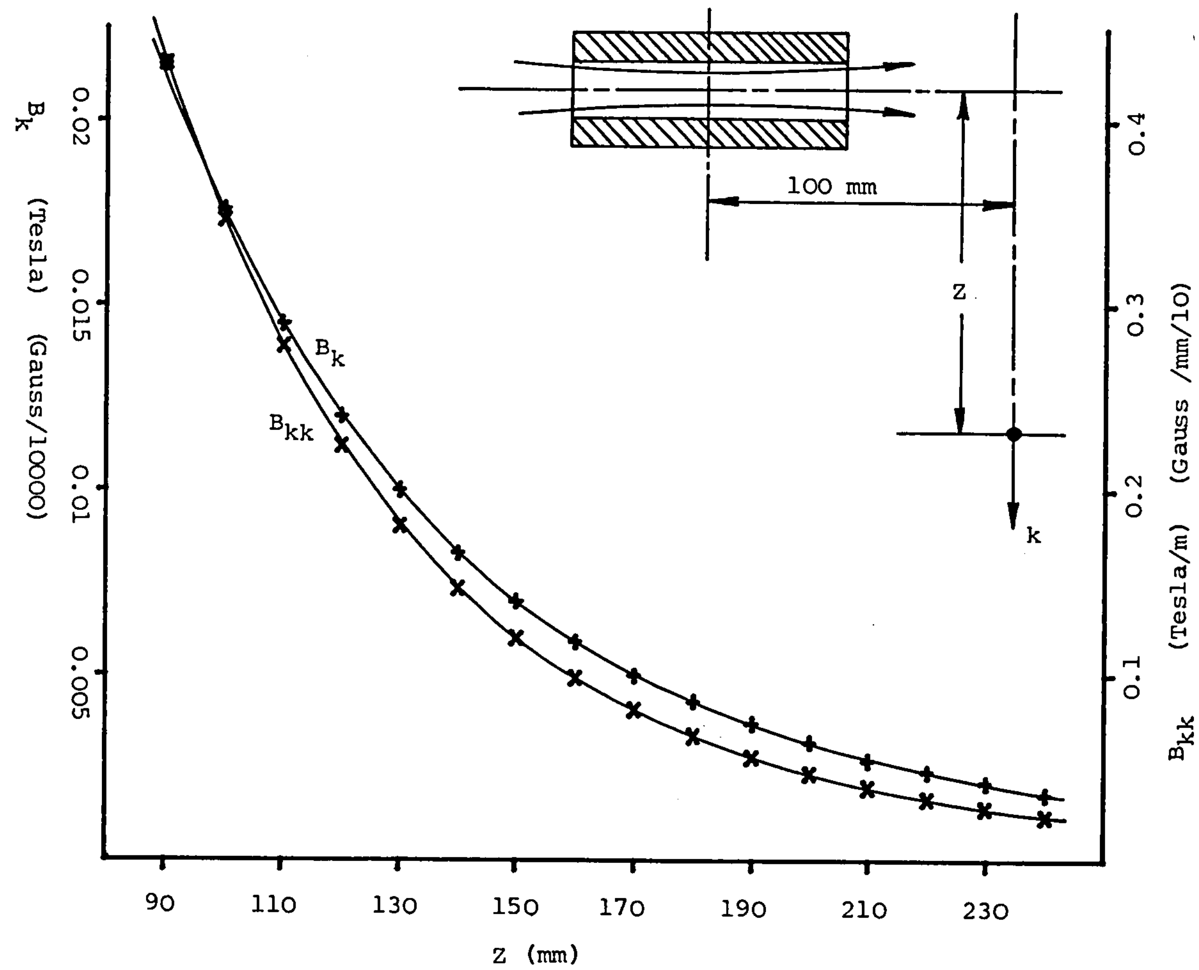
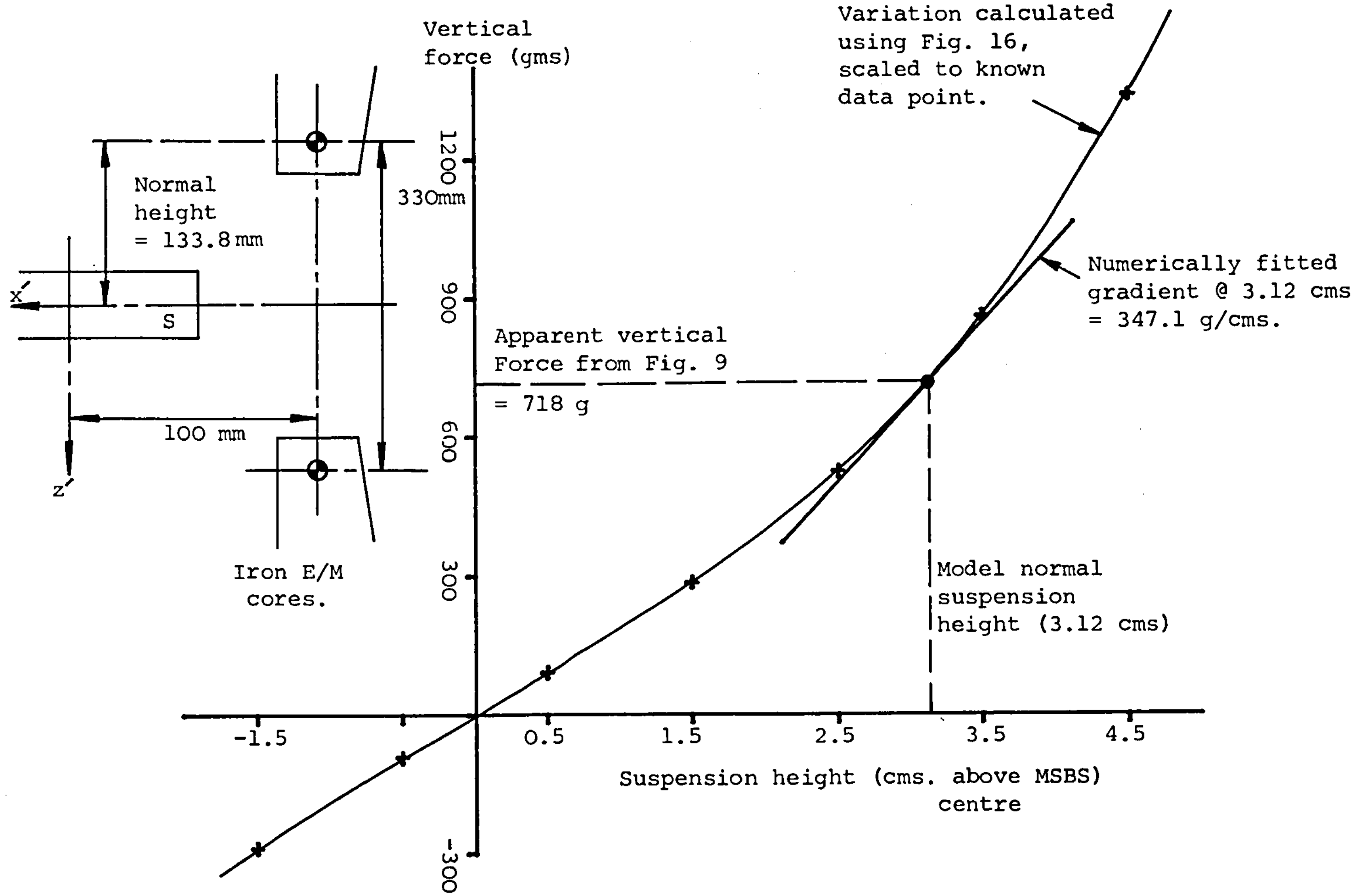


Fig. 17: Predicted variation of stray vertical force with suspension height



2.3. Helium boil-off measurements

In-suspension boil-off measurements were made by attaching a gas flow meter via a long flexible pipe to the helium gas vent. A slowly increasing boil-off with time was measured. This is somewhat surprising, if a real effect. Model pitch attitude changes or vertical oscillations produced no dramatic variations (Fig. 18). Increased boil-off with the vent end "low" and vice versa corresponds to expectations and previous measurements (Ref. 2). Oscillations of the external field, hence model, would be expected to provoke eddy currents in the inner dewer, perhaps also the superconductor itself, and sloshing of the LHe, all resulting in increased heat load into the LHe.

High magnetic force measurements were made (in a later run) with the model lowered onto a rubber support pad on the test section floor. The previous force/current calibration can only be expected to apply approximately in this case but the general results are of interest (Fig. 19). The increased boil-off at high loads may be related to distortion of the inner dewar support structure and consequent compressive loading of the superinsulation (See Fig. 2). The model was not designed with such high loadings in mind (over 5 times the all-up weight), but appears to have survived undamaged.

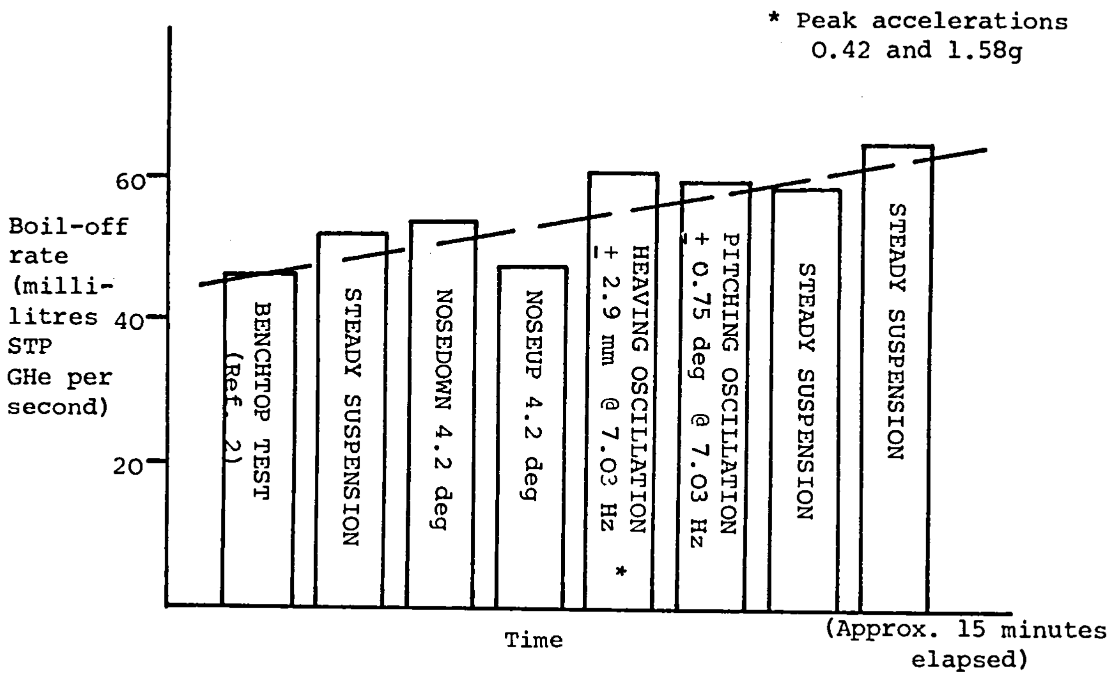


Fig. 18: In-suspension helium boil-off measurements

1 mW heat soak into LHe corresponds to around 0.27 ml STP GHe per second

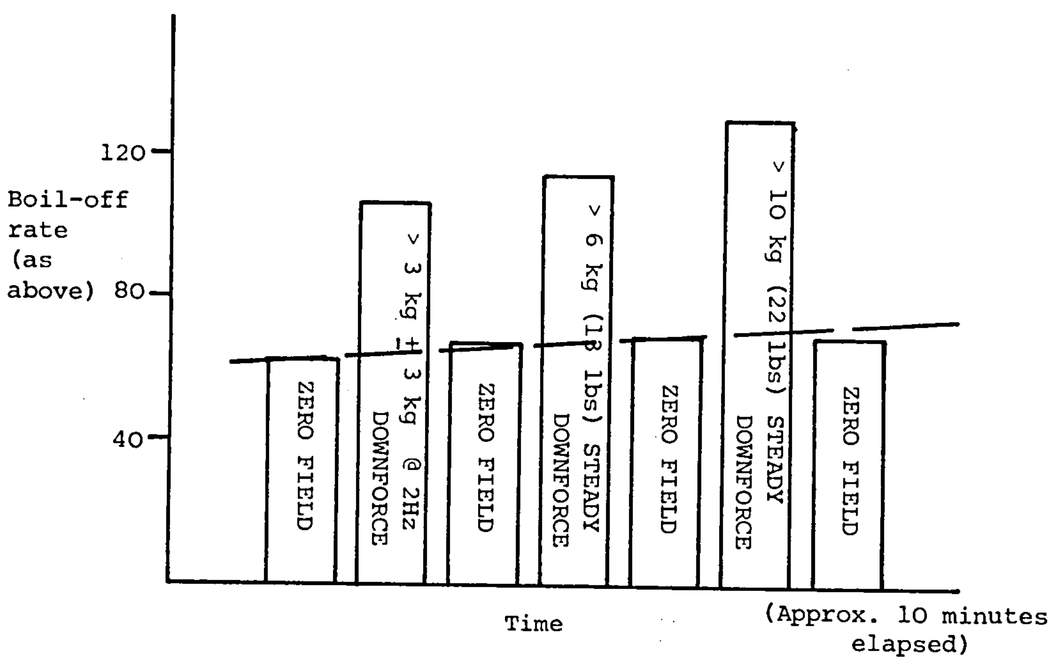


Fig. 19: High magnetic force helium boil-off measurements

3. DISCUSSION AND CONCLUSIONS

The pilot superconducting solenoid model has comfortably met all original specifications and, indeed, has proven to be unexpectedly robust, surviving application of considerable magnetic forces, quite severe forced oscillations and even loss of suspension control and a subsequent "crash" (probably MSBS operator error), with no evidence of conductor quenching or mechanical or electrical failure. No problems of control stability were encountered, the model behaving indistinguishably from a large permanent magnet. These facts enhance confidence in the fundamental concept.

The model should in no way be regarded as representing the best contemporary technology. The magnetic moment/unit volume is not high, the superconducting life between LHe fills not especially long and the mechanical design not especially robust. Nevertheless, it is clear that reasonable revisions or improvements in design such as:

a) Increasing proportion of overall volume occupied by solenoid windings.
b) Optimisation of solenoid geometry (high o.d.)
c) Increased sophistication of mechanical supports of inner dewar/ solenoid.
d) Increased sophistication of thermal design
e) Use of higher current density superconductor.

could together considerably raise performance at this scale, to at least equal the total magnetic moment of the best equivalent permanent magnet core, with life between LHe fills being no real restriction. With the natural improvement in performance at larger scales (over twice present scale for an 8 foot tunnel) and bearing in mind that the required thicknesses of thermal insulation tend to remain fairly independent of scale, it may be concluded that the superconducting solenoid concept, with existing conductor and cryogenic technologies, represents a realistic alternative to ferromagnet cores at least on the basis of magnetic moment/unit volume. Other considerations, such as the provision of roll control methods of power commensurate with that of the main model core or the reliability of a superconducting solenoid core, remain to be addressed in this context.

The quality of static calibrations performed was considered good. The attempted dynamic calibration was rather less successful, largely due to the realisation, after the event, that substantial stray lift forces and vertical stiffnesses were unaccounted for. The distorted current waveform of Fig. 13,

ideally sinusoidal of course, may be due to the non-linearity of these stray effects (see Fig. 17) or other causes. Induced eddy currents in the model are viewed as a potential distorting factor in this type of procedure, with magnetic relaxation times, in this case in the iron E/M cores, also a matter for concern. Further analysis is not appropriate here but more detailed study of dynamic calibration techniques will soon be commencing.

The variations in LHe boil-off with model motion and applied forces are considered acceptably low. Over one hour of suspension time has been accumulated to date.

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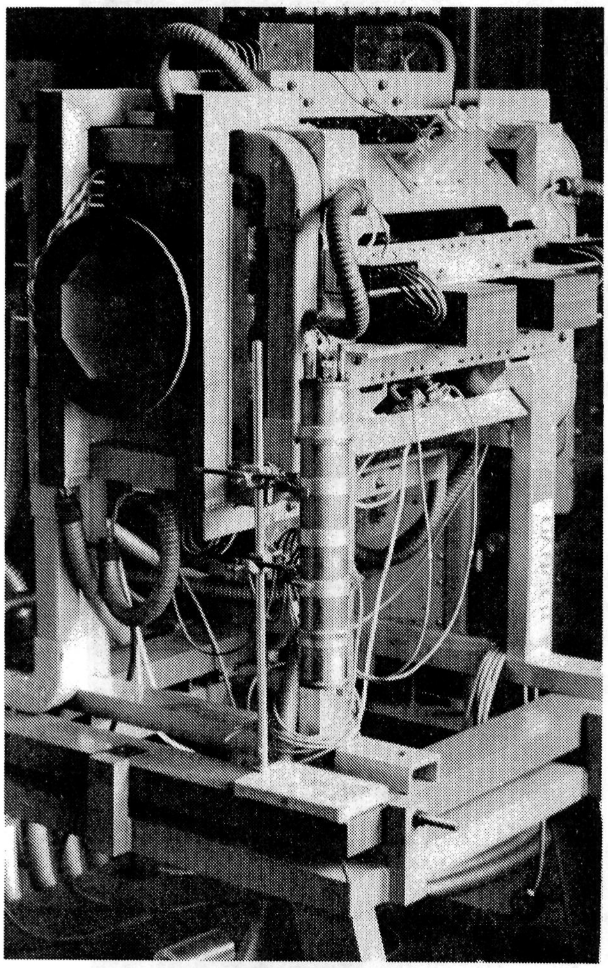
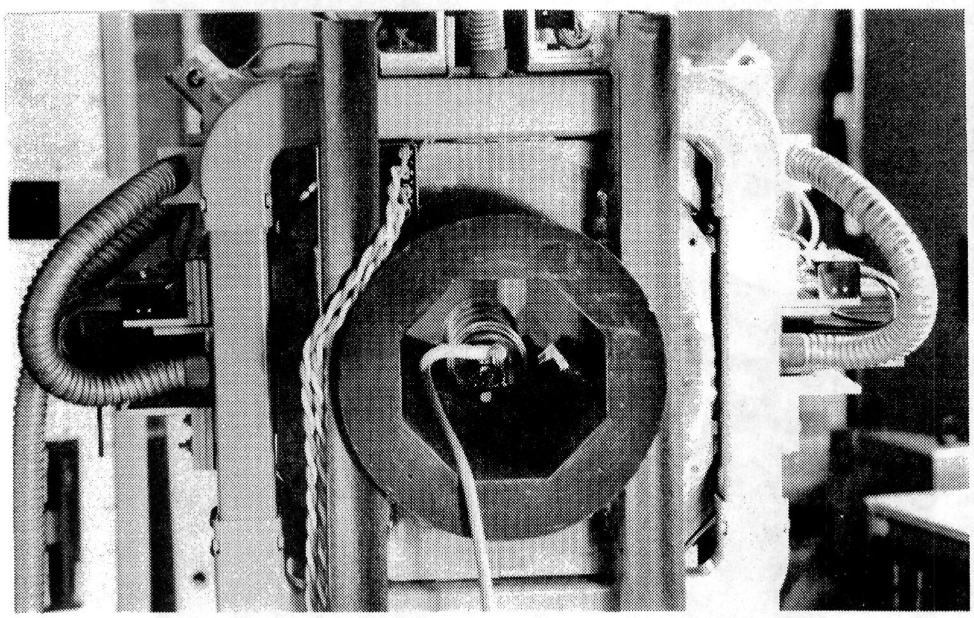
PLATES

These plates are not specifically referenced in the text but are included for background information.

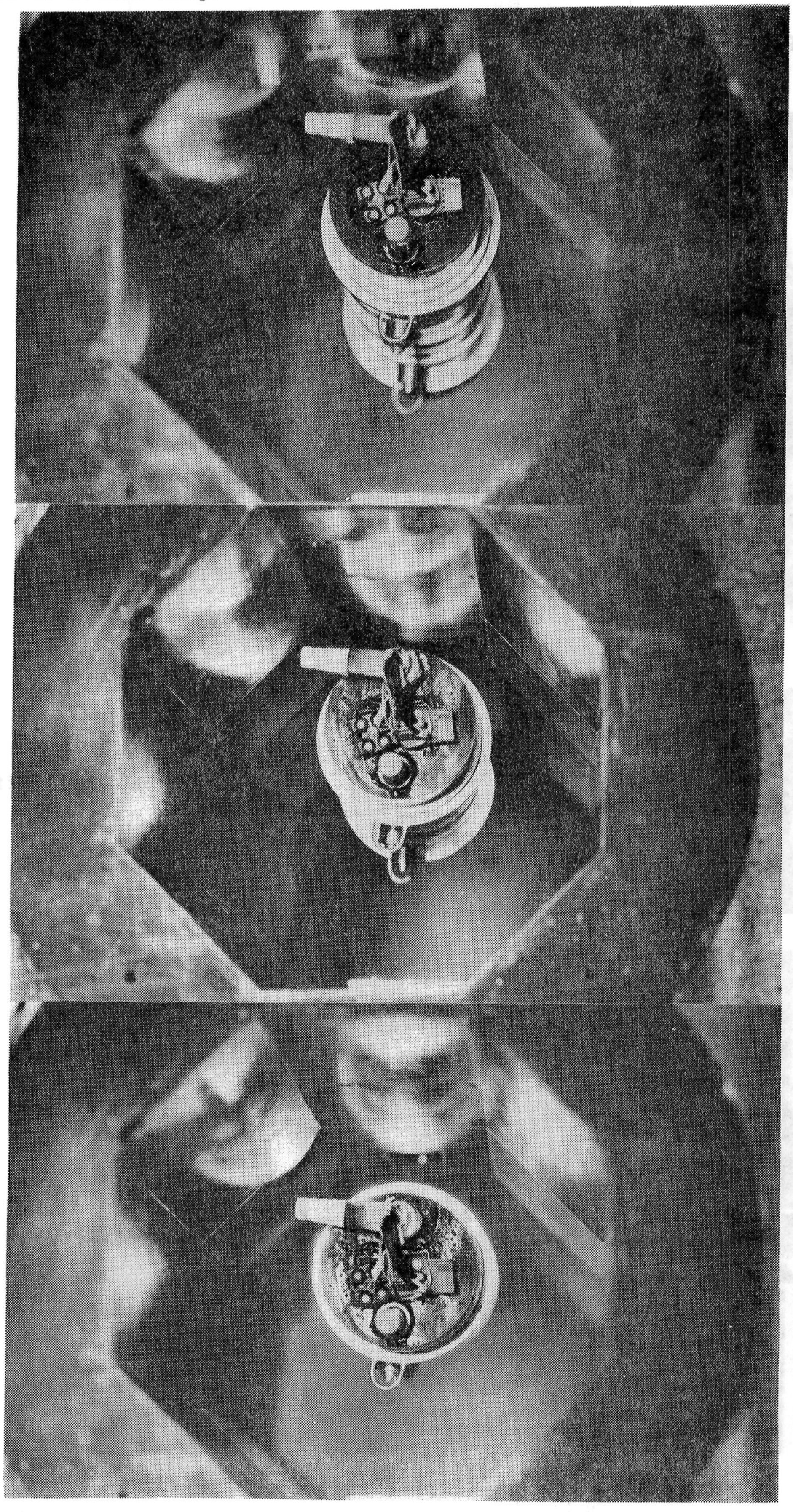


Model and SUMSBS

High field boil-off tests



Angle of attack range



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16. Abstract

Persistent superconducting solenoids may offer higher model magnetic moments than conventional ferromagnetic cores in large scale wind tunnel magnetic suspension and balance system (MSBS), thereby achieving economics in suspension electromagnet and power supply size and cost.

An experimental superconducting solenoid model core has been built and demonstrated with the Southampton University MSBS. Initial performance and calibration data verifies the technical feasibility of this model core concept.

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